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Space weather event of 25 September 1998: Ionospheric Response

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ABSTRACT
Ground geomagnetic data at a chain of stations in India, interplanetary magnetic field, solar wind parameters and the ionospheric data at Thumba are examined to study the great geomagnetic storm of 25 September 1998. The geomagnetic storm is unique because of the strong counter electrojet in the morning, strong electrojet around noon and then counter electrojet in the afternoon hours caused by the enhanced solar wind density and velocity in association with the changes in IMF Bz. Disappearance of Esq in the morning hours, absence of ionization anomaly in the pre-noon hours, strong ionization anomaly near noon and later the absence of the post-sunset height rise and equatorial spread-F on 25 September 1998 are observed as a consequence of the imposition of electric fields associated with the space weather event.

INTRODUCTION

Earth's atmosphere, neutral as well as ionized, is influenced greatly by the solar activity. In addition to the regular slowly varying changes with solar activity there are dramatic events like solar flares and coronal mass ejections that give rise to the geomagnetic storms and the changes in the upper atmosphere-ionosphere-magnetosphere. The high latitudes are sensitive to the solar charged particle precipitation during disturbed conditions, whereas the low latitudes are protected from the particle precipitation, especially in the Indian longitude sector where the geomagnetic field is close to the highest. However the equatorial electrojet within $\pm$ 3^o around the dip equator is very sensitive to any small change in the electric fields of magnetospheric origin. The electric fields of magnetospheric origin not only affect the ionosphere at high latitudes but also penetrate to low latitudes causing changes in the ionosphere-thermosphere there. The changes in the ionosphere that follow the geomagnetic storms could result in severe scintillations that disrupt radio communications and/or cause large changes in ionization that can over/under estimate the ionospheric corrections required in some applications. Therefore there is need to understand and predict the ionospheric effects of such events.

There have been numerous studies related to the geomagnetic storm effects in the density, composition and dynamics of the sub-auroral, middle and low latitude ionosphere and thermosphere *e.g.* Rajaram, Das & Rastogi (1971), Rastogi (1989), Kelley (1989), Fuller-Rowell *et al.,(*1994), Basu *et al*. (2001), Fejer (2004). Prompt penetration and disturbance dynamo electric fields, though of smaller magnitude, are the important sources of low latitude ionospheric electrodynamics disturbances. Sharp electric field perturbations with time scales typically shorter than about an hour are due mostly to the prompt penetration of solar wind/magnetospheric electric fields to middle, low and equatorial latitudes (Fejer 2004). Quasi-period (DP2) magnetic field fluctuations with time scale of about half an hour to several hours at high latitudes and in the dayside of magnetic equator are signatures of convection electric fields controlled by IMF B_Z (Nishida 1968). Rastogi & Chandra (1974) first reported the association between the IMF Bz and the ionospheric drifts near dip equator, a measure of the electric field in ionosphere. Rastogi & Patel (1975) noted large and quick changes of the IMF Bz from southward to northward direction are associated with the reversal of ionospheric electric field over Jicamarca. Slower varying electric field disturbances with time scales of few hours to tens of hours are identified as ionospheric disturbance dynamo electric fields caused by enhanced energy deposition in to the auroral ionosphere e.g. Blanc & Richmond (1980).

Features of Low Latitude Ionosphere

Electrodynamics plays an important role in the equatorial and low latitude ionosphere (Rastogi et al., 1972, Abdu 1997, Rastogi & Chandra 1999). The configuration of the northward magnetic field and zonal electric fields of dynamo origin give rise to special features of the ionosphere at low latitudes. These are,

Equatorial Electrojet and Equatorial E_s

Intense daytime eastward current that flows in the E-region in a narrow band of latitudes centered over the dip equator named 'Equatorial Electrojet' by Chapman (1951). This is caused by the enhanced conductivity resulting from the vertical Polarization field close to the dip equator where the electric and magnetic fields are orthogonal to each other (Baker & Martyn 1953). There are occasions when the westward current flows during the daytime due to the electric field reversals. Such events are known as counter electrojet. Associated with the equatorial electrojet is the regular daytime transparent type of sporadic-E that appear from the scattering from plasma density fluctuations present due to plasma instabilities that operate near the magnetic equator arising from the two-stream instability and the cross-field instability mechanisms. During periods of daytime counter electrojet when electric field reverses as indicated by the reversal of ionospheric drift from westward to eastward, the equatorial type of sporadic-E also disappears (Rastogi, Chandra & Misra 1971).

Equatorial F_2-Anomaly

The zonal electric fields map into the F-region of the ionosphere along the highly conducting geomagnetic field lines and uplift the plasma. The vertical transport of plasma from equatorial region followed by the diffusion along geomagnetic field line gives rise to ionization peaks at latitudes of ± 20° magnetic latitudes. This latitudinal distribution of plasma density in the F-region is also known as Equatorial anomaly or Appleton anomaly. In the daily variation of plasma density near magnetic equator this is seen as midday bite out. The equatorial anomaly is related to the electrojet strength (electric field) and suppressed during the periods of counter electrojet.

Equatorial Spread-F

The low latitudes are marked with high incidence of spread-F (spreading of echo trace in ionograms) during nighttime. The equatorial spread-F (ESF) is associated with the post-sunset uplift of the F-region due to the action of eastward electric field and plasma density gradients in the lower F-region of the ionosphere. Plasma density irregularities covering a wide range of scale sizes, extending from hundreds of km to a fraction of a meter are associated with the phenomenon of ESF. The generalized Rayleigh-Taylor instability, that includes the electric field and neutral winds along with gravitational term, is considered to be the primary process for the generation of intermediate scale irregularities. Large-scale plasma depletions thus generated rise fast to cover entire F-region including topside. Steep plasma density gradients then provide seat for the generation of small-scale irregularities (Haerendal 1974). The plasma density structures also give rise to intense scintillations of radio waves propagating through the ionosphere.

Geomagnetic storm effects in Ionosphere/ Thermosphere at low latitudes

The features of low latitude ionosphere during geomagnetic disturbed conditions are fairly well known. The electric fields are weakened and during some of the geomagnetic storms even reversed. Spaced receiver drift measurements from Thumba showed decrease of the zonal drift speed with magnetic activity (Rastogi, Chandra & Misra 1971). VHF back-scatter radar measurements from Jicamarca also indicate reduced drift velocity on magnetically active days (Fejer 1997). The electric field reversals that are seen during daytime on some occasions give rise to counter electrojet events and the disappearance of the q type of sporadic E (Rastogi, Chandra & Chakravarty 1971). During geomagnetic storms, interaction of the solar wind with IMF Bz gives rise to electric field that is transmitted to low latitudes and prominent effect is seen in the electrojet due to the enhanced conductivity (Chandra & Rastogi 1997).

Equatorial F_2 region anomaly is generally weakened or absent on geomagnetic disturbed days (Rastogi et al., 1972, Deshpande et al., 1977, Rastogi & Klobuchar 1990). Equatorial spread-F is inhibited in general except during the June solstices of low solar activity periods when an increase is noted (Chandra & Rastogi 1972). However some of the geomagnetic storms are associated with intense spread-F (Rastogi & Woodman 1978). On occasions strong scintillations associated with spread-F, generated in the early morning hours, extend to daytime hours also (Vats et al., 1978, Chandra et al., 1995). Aarons (1991) from daytime scintillations near magnetic equator at different longitudes concluded that scintillations get enhanced, inhibited or unaffected if the maximum excursion in Dst occurs during post-midnight, afternoon and sunset hours respectively.

There have been a number of case studies of the response of the equatorial ionosphere to major space weather events covering equatorial ionization anomaly, equatorial spread-F and scintillations (Sastri et al., 2000; Sastri, Niranjan & Subba Rao 2002; Basu et al., 2001, 2007; Kumar et al., 2005; Abdu et al.. 2007; Tulasi Ram et al. 2008; Veenadhari et al., 2010).

A major space weather event occurred on 25 September 1998 with sudden commencement at 2345 UT (0445 LT) corresponding to the time of maximum dawn – dusk electric field. Clauer, Belenkaya & Baker. (2001) and Bobrovnikov et al., (2005) have described the features of this storm. Arrival of a dense cloud of the solar wind plasma at 23.45 UT on 24 September was accompanied by a northward turning of the IMF, remaining in this direction for 1 h 45 min leading to a significant decrease of the polar cap for 30 min. After 01.30 UT the IMF had a strong southward component. Moreover, at 06.00 UT on 25 September the second shock wave of the solar wind dense plasma encountered the magnetosphere. At almost the same time a significant substorm activity was detected.

This paper describes the geomagnetic field variations at a chain of stations in the Indian region covering from dip equator to the Sq focus, Interplanetary magnetic field and solar wind parameters during the space weather event and associated effects in the ionosphere at Thumba (Geog. Lat 8.5^o N, Geog. Long 77.0^o E, inclination) situated close to the magnetic equator.

RESULTS

Space weather event of September 1998: Geomagnetic observations

The geomagnetic storm of 25 September 1998 was unique event considering the relatively quiet conditions over the years 1997-99. A plot of the daily average index Ap over the three years period in Fig. 1 shows hardly any value exceeding 50 nT during the entire year of 1997. During the year 1999 also there are only three values of Ap more than 50 nT. During the year 1998 there are few Ap values of more than 50 nT and just three values of more than 75 nT. Thus 25 September 1998 with Ap of about 140 nT is the only major geomagnetic disturbed event over this 3 year period.

The variations of the solar wind parameters (density, speed and flow pressure) and the southward component of the interplanetary magnetic field from satellite measurements (ACE, WIND, IMP8; website OMNI) on 24 and 25 September 1998 are shown in Fig. 2 in UT. Also shown in the figure are the

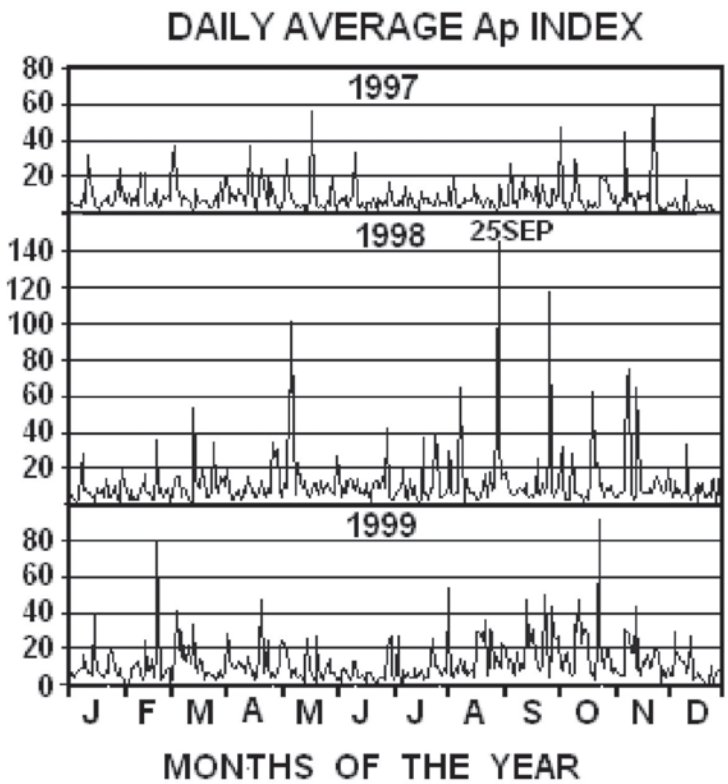


Figure 1. Daily average value of Ap index for each of the day of years 1997, 1998 and 1999.

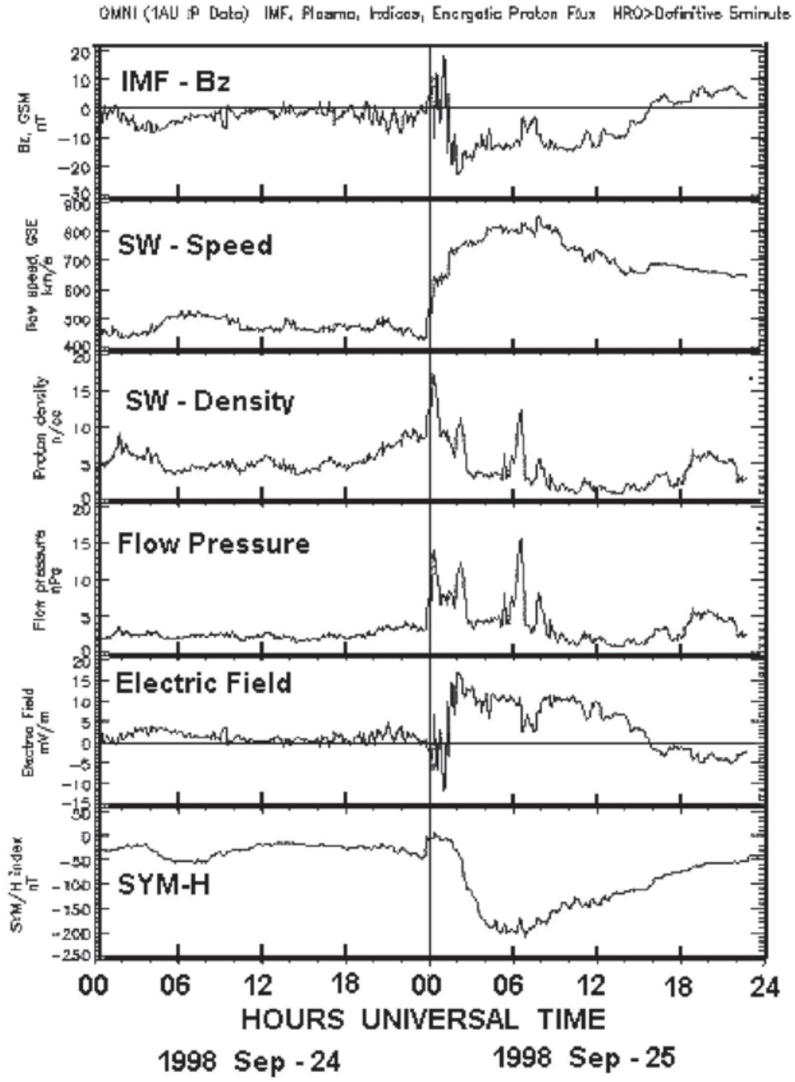


Figure 2. Daily variations of the hourly values of IMF Bz, solar wind density, solar wind velocity, flow pressure, interplanetary electric field (-VxBz) and SYMH on 24 and 25 September 1998 (UT).

computed interplanetary electric field (-VxBz) and SymH values. A strong interplanetary shock crossed the WIND spacecraft (about 185 RE upstream of Earth) at 2320 UT on September 24, 1998. B_Z component of IMF remained within 0-10 nT southward on 24 September 1998. However it turned northward for a while on 25 September 1998 (00-0130h UT) and then turned negative sharply reaching a value of more than -20 nT at 03 UT, remaining negative till 15h UT. The solar wind speed was less than 500 km/s on 24 September 1998. It increased sharply and reached peak value of about 850 km/s at 08h UT and remained high throughout the day. Solar wind density also increased from the values of about 5 cm^{-3} to about 15 cm^{-3} with peaks around 00h, 02 h and 06h UT. The solar wind pressure applied to the nose of magnetosphere jumped at 2344 UT from about 2 nPa to almost 15 nPa. The peaks of solar wind pressure are seen around 00h, 02h, 06h UT. The computed interplanetary electric field (-VxBz) shows a value of about -10 mV/m just after 00 UT and then turning to positive values around 0130h UT and reaching a peak value of 15 mV/m at 02h UT. High positive values are seen during the period 02-06 h UT and then 08-12h UT. The values dropped to near zero between 06 and 08h UT. The SymH values show small sudden increase at 2345 UT followed by large decrease to a value of -200 nT at 06h UT.

The hourly values of the geomagnetic H component after subtracting the monthly mean Sq variation of H at a chain of stations in India, Trivandrum (TRD) located close to dip equator; Etiapuram (ETT) and Kodaikanal (KOD) in the electrojet region; Pondicherri (PON) just outside the electrojet region; Hyderabad (HYD), Alibag (ABG), Ujjain (UJJ) away from the dip equator and Sabhawala (SAB) near the Sq focus for 24-25 September 1998 (UT) are shown in Fig. 3. Hourly values of the Dst index is also plotted in the figure. The variations are similar at all the stations with no significant changes on 24 September 1998. A sudden commencement, SC, occurred at 2345 UT, which corresponds to 0445h LT (75^o EMT) and is associated with the arrival of the dense cloud of solar wind plasma as seen in the sudden increase of solar wind velocity and density in Fig. 2. It was interesting to note that the amplitude of ΔH (SC) was stronger at stations away from the dip equator than at the equatorial station TRD. Following the SC there is a sharp decrease in H of about 200 nT, associated with the southward turning of the IMF Bz. The hourly values of the geomagnetic Y component after subtracting the Sq for all the stations is also shown in the figure (right panel). There is not much of variation in Y component on 24 September 1998 but following the SC there is an increase in Y component at all the stations (barring ETT). The amplitude of the Y component is smallest near dip equator and increases with latitude with maximum at SAB near Sq focus.

The tracings of the H magnetograms for 25 September 1998 at TRD (equatorial electrojet station) and UJJ (away from equatorial electrojet) are reproduced during 06-21 hr LT in Fig. 4. The tracings for the two stations are superimposed so that differences can be easily noted. The difference between the ΔH at an equatorial electrojet station and at a station away from the equatorial electrojet station is a good index of the strength of equatorial electrojet. The values of ΔH after the SC were consistently smaller at TRD than at UJJ up to 0900h LT (04 UT) suggesting the existence of counter electrojet (westward electric field). Closer examination shows the signature of CEJ starting at 0130 UT (0630 LT), no CEJ during 0150-0200 UT and then CEJ starting again at 0200 UT with peak at 0245 UT. The CEJ almost disappears at 0310 UT when the ΔH values are equal at the two stations. From 09h (04 UT) to 11h (06 UT) the values of ΔH at TRD are higher than at UJJ suggesting normal electrojet. There is another counter electrojet for a brief period of 1115-1130h (0615-0630 UT) and then again normal electrojet is seen from 1230h (0730 UT) to 1500h (1000 UT). From

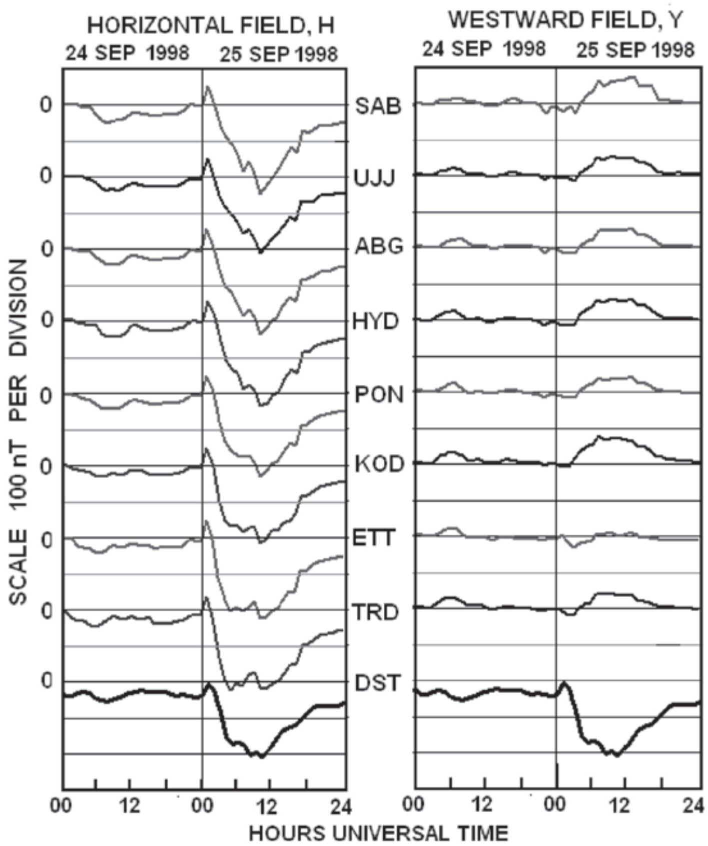


Figure 3. Daily variations of the geomagnetic H field and westward field Y on 24 and 25 September 1998 (UT) at a chain of stations in India covering from TRD near dip equator to SAB near Sq focus.

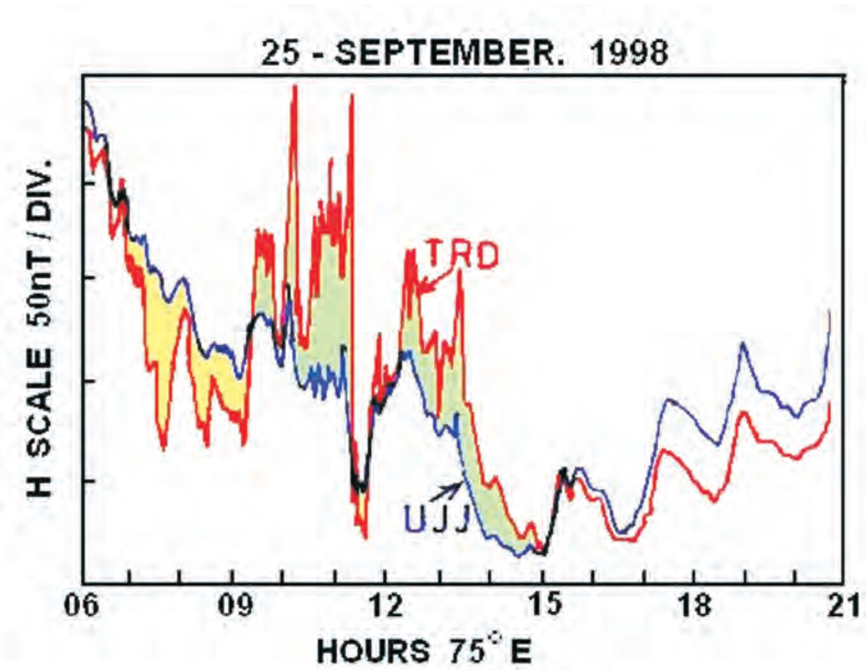


Figure 4. Copy of H magnetograms at TRD (dip equator) and UJJ (away from the electrojet region) for the period 06-21 h (LT) on 25 September 1998.

1500h (1000 UT) onward the values of ΔH are again lower at TRD indicating another counter-electrojet. Thus the day is unique with counter-electrojet in the morning hours till 0900 LT, normal electrojet in pre-noon hours followed by a weak short duration counter electrojet just before midday, normal electrojet between 12-15h LT and then another counter-electrojet.

The geomagnetic H variations, after subtracting the Sq variation and Dst, at a chain of Indian stations, right from Trivandrum (TRD) at magnetic equator to Sabhawala (SAB) near Sq focus, are plotted for 24-25 September 1998 (UT) in Fig. 5. Subtracting the Sq variation at a station removes the contributions from the ionospheric currents while subtracting Dst values removes the contributions from the ring current. The residual then may be considered due to the magnetic storm effects. The variations on 24 September are similar at all stations barring the electrojet stations of KOD, ETT and TRD. A decrease of about 40 nT from 00 UT to 12 UT and then increase to 00 UT is seen. At electrojet stations the decrease after 00 UT is followed by an increase with peak around 08h UT. The magnitude of the peak is little higher for TRD than at ETT and KOD. The variations on 25 September are also different at stations in the electrojet region. At TRD there is a sharp dip in the value from 00 UT to 02 UT of more than 80 nT. The dip lasts till 06UT and then there is rapid increase of 60-70 nT with maximum around 08 UT. This is followed by another large decrease of about 80 nT with minimum at 12 UT. The value recovers slowly from midday to around 17h UT. Almost similar features are seen at ETT with magnitudes of the decreases/increases little lower in magnitude. At KOD also these features are seen with little lower magnitudes but one can see small minor peak around 04 UT. At PON, just outside the electrojet region, the magnitudes of decreases/increases become still lower. At stations HYD, ABG, UJJ and SAB the features are similar. The prominent dip after midnight is missing and the minor peak around 03-04 UT becomes very prominent. However the second dip at 12 UT is noticed at all the stations with almost similar magnitude. Thus the magnetic storm event points to strong counter electrojet around 02-07 UT, weak normal electrojet between 07-09 UT and then again a strong counter electrojet from 09 to 17 UT.

Dst index is derived from the geomagnetic data at stations near the sq focus located in different longitude sectors. This may not always represent the ring current effect at a particular longitude sector. The ring current effect has a latitudinal variation, increasing as a secant of the geomagnetic latitude of the station. Within equatorial and low latitudes this change is not significant. We assume that SqH at

Sabhawala would be more appropriate index of the ring current for the Indian longitude sector. Therefore we have also examined the difference of the hourly values of H component after subtracting the SqH, at a station and hourly values of H component after subtracting the SqH values at SAB for remaining stations ({H – SqH}station – {H – SqH}SAB) and plotted in Fig. 6. The diurnal pattern shows clearer picture compared to Fig. 5 where SqH and Dst were subtracted. On 24 September a dip at 03 UT and maximum at 09 UT are seen very clearly at electrojet stations with magnitudes decreasing with latitude. Non equatorial electrojet stations do not show any significant variations. On 25 September large dip centered at 04 UT, maximum at 09 UT and second dip at 15 UT are seen clearly. The magnitude is largest at TRD and decreases systematically at ETT, KOD and PON. Thus subtracting the Sq value at Sabhawala apart from the Sq value of the station provides a better method to study the effect of geomagnetic storms. The changes seen on 25 September at electrojet stations then are solely due to the electric fields imposed because of the IMF and solar wind.

The strong counter electrojet around sunrise is due to the dusk-dawn electric field generated by to the action of the rapid decrease of IMF B_Z simultaneously with the rapid increase of solar wind velocity. This effect is superimposed on the effect due to decreasing Dst index caused by the development of the disturbance ring current. The dusk-dawn electric field decreased when the gradient of IMF B_Z as well as solar wind velocity became steady. Thus the unique case of the counter electrojet in the morning of 25 September 1998 is not the late reversal of electric field but a counter electrojet due to the space weather event. Looking at the geomagnetic field variations on 25

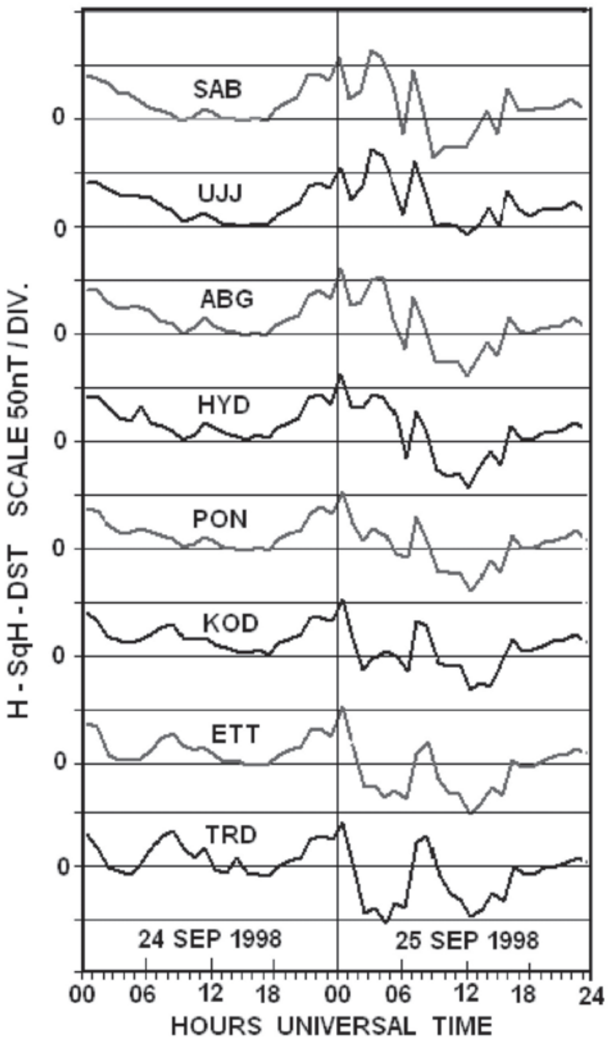


Figure 5. Daily variations of the hourly values of the geomagnetic H component after subtracting the SqH and Dst values at a chain of stations in India on 24 and 25 September 1998 (UT).

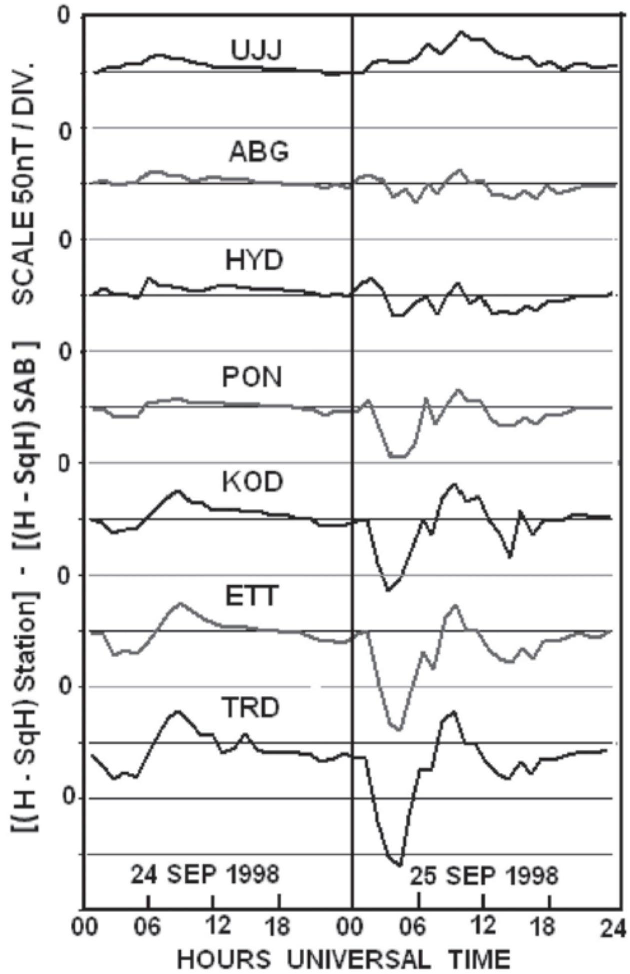


Figure 6. Daily variations of the difference of the hourly values of the geomagnetic H component after subtracting the SqH at the station and the hourly values of the H component after subtracting SqH at SAB ({H – SqH}station – {H – SqH}SAB) for the chain of other stations in India on 24 and 25 September 1998 (UT).

September 1998, after the strong counter electrojet in the morning hours (0130 UT-0400 UT) there is normal electrojet around noon (04-06 UT; 0730-1000 UT) and then another counter electrojet in the late afternoon hours (after 1000 UT). The sudden turning of IMF to southward just before the sunrise along with enhanced solar wind velocity gives rise to the morning counter electrojet. Reduced southward IMF (-15 to -5 nT) and enhanced solar wind velocity give rise to normal electrojet condition around noon. In the afternoon hours southward component of IMF again increases and with enhanced solar wind velocity cause counter electrojet. Thus the day is unique in the sense that electric field changes in the morning, around noon and then in the afternoon.

The hourly values of "H after subtracting Sq and Dst at few selected stations in the electrojet region at different longitudes are shown in Fig. 7 plotted in UT. The local noon, sunrise and sunset at each station are also marked with the arrow. The IMF Bz component is also plotted in the figure. The southward turning of the Bz around 00 UT is associated with the counter electrojet in the pre-noon hours (LT) at TRD. The counter electrojet is strongest in the Indian longitudes, weaker at AAE in African sector and not seen at MBO and TTB due to the night hours there. The second counter electrojet is seen in the afternoon at TRD as a weak event and is strongest at AAE as it happens there around local noon. Its magnitude decreases at MBO and TTB. The normal electrojet that is seen around noon at TRD increases in magnitude and is largest at TTB.

Ionospheric observations

The critical frequency of the F_2 region, f_oF_2, the minimum virtual height of the F-layer, h'F and the virtual height at a frequency 0.834 of f_oF_2, known as

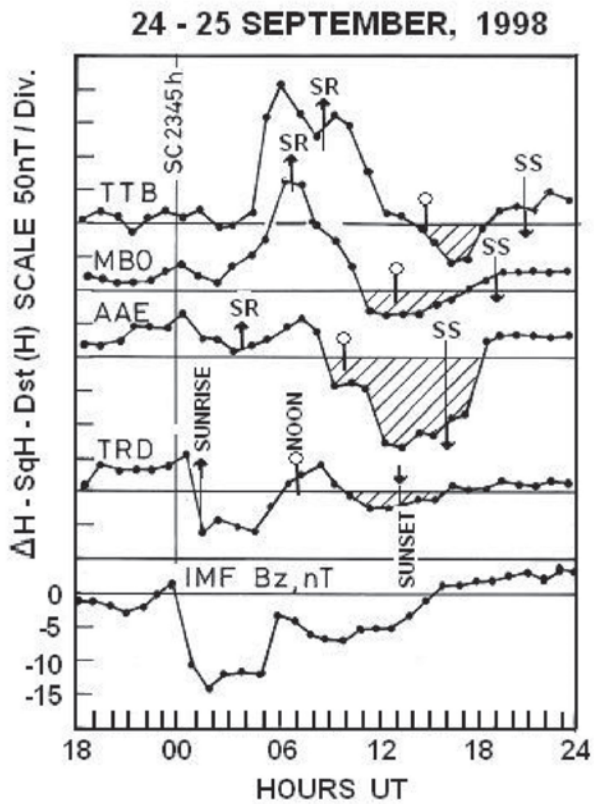


Figure 7. Daily variations of the hourly values of the geomagnetic H component after subtracting the SqH and Dst values at a chain of electrojet stations in different longitudes from 18h of 24 September to 24h of 25 September 1998 (UT). IMF Bz is also plotted.

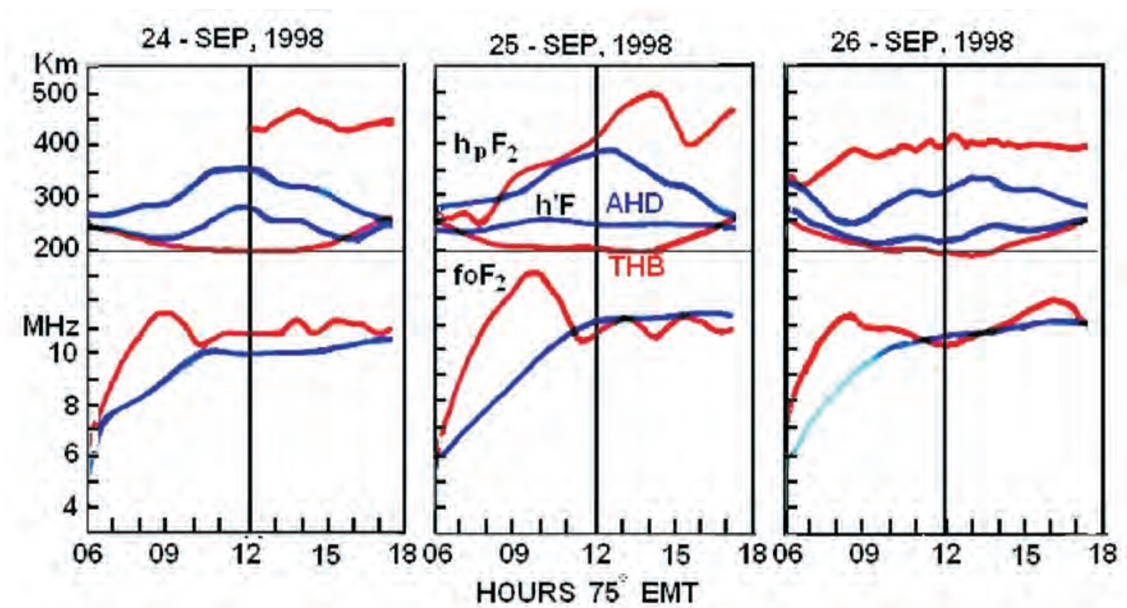


Figure 8. Daily variations of the critical frequency of F_2 layer (f_oF_2), minimum virtual height of F-layer (h'F) and the virtual height of F_2 layer at 0.834 of f_oF_2 (a measure of the height of maximum ionization) at Thumba, near magnetic equator and at Ahmedabad, near the anomaly crest region on 24, 25 and 26 September 1998 (LT).

h_pF_2, which is a measure of the height of maximum ionization in F_2 layer are plotted during daytime hours of 24-26 September 1998 for Thumba near dip equator and Ahmedabad near anomaly crest region in Fig. 8. h_pF_2 is a measure of the height of maximum electron density in F-region under the assumptions that the layer is parabolic and there is no underlying ionization. Comparative studies have shown that h_pF_2 is a fairly good indicator of the height of maximum ionization. It correlates very well during night time but slightly overestimates during daytime (Shirke 1963, Chandra & Sharma 2000). However this will not affect the comparison on a day-to-day basis. The variations of the F-region parameters for 26 September 1998 are typical. The h′F decreases after sunrise with minimum at noon and again increasing. h_pF_2 decreases initially after sunrise and then increases with peak near noon. The critical frequency shows a bite out at noon with two peaks in the morning and afternoon at Thumba and peak in the afternoon for Ahmedabad. However on 25 September 1998 there are distinct differences. The variation of h′F appears like on 26 September 1998 but h_pF_2 over Thumba shows rapid increase from noon reaching to 500 km around 14-15h compared to values of around 400 km on 26 September 1998. The h_pF_2 values over Ahmedabad also show little higher values around this time on 25 September 1998. The major difference in the daily variations of f_oF_2 on 25 September is seen before noon. From 07h to 11h the values at Thumba are larger than on 24 and 26 September 1998. The peak value of f_oF_2 at 10h on 25 September 1998 is about 13 MHz compared to 11 MHZ on other two days. The f_oF_2 values for Ahmedabad between 07h and 10h are lower than the values on other two days. Thus the higher values of f_oF_2 at Thumba and lower values at Ahmedabad between 06-11h of 25 September 1998 are due to the counter electrojet event associated with the space weather event. In the afternoon hours the values are little higher or equal at Ahmedabad on 25 September compared to other two days. The evening peak of f_oF_2 at Thumba around 17h is not seen on 25 September 1998. There is another minor dip, though not prominent, in the daily variation of f_oF_2 at Thumba on 25 September 1998 around 1430h. This is associated with the large increase in the height of maximum of F_2 layer in the afternoon over Thumba. Fig. 9 show selected ionograms at Thumba in the pre-sunrise hours on 24 and 25 September 1998. The ionograms show f_oF_2 decreasing from about 3 MHz at 0415h to 2.2 MHz at 0515h. The value increases to 3.4 MHz at 0530h and to more than 4 MHz at 0545 h. On 25 September also the f_oF_2 values decrease from 0415h to 0500h similar to 24 September. But the ionogram of 0515h shows a new F-layer appearing at a height of 500 km.

The ionograms in the sunrise hours for the two days are shown in Fig. 10. The ionogram traces at

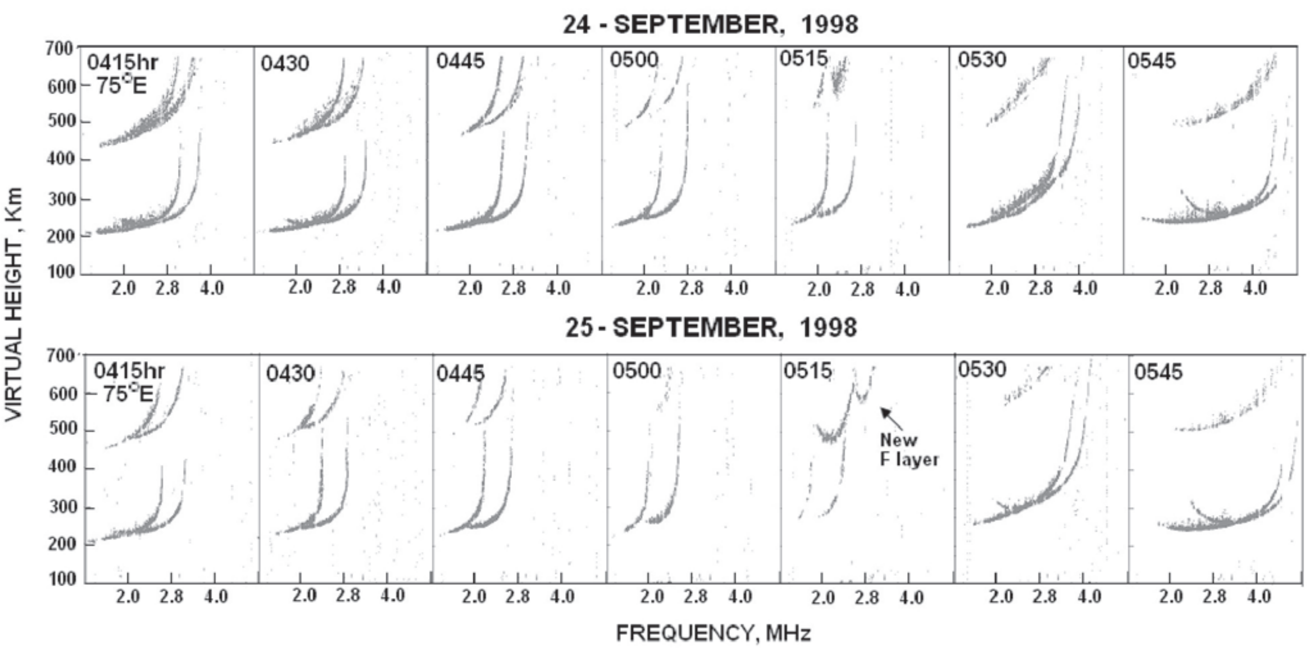


Figure 9. Quarter hourly ionograms from 0415h to 0545h (LT) at Thumba on 24 and 25 September 1998. A new F-layer is seen at 0515h on 25 September 1998 around 600 km.

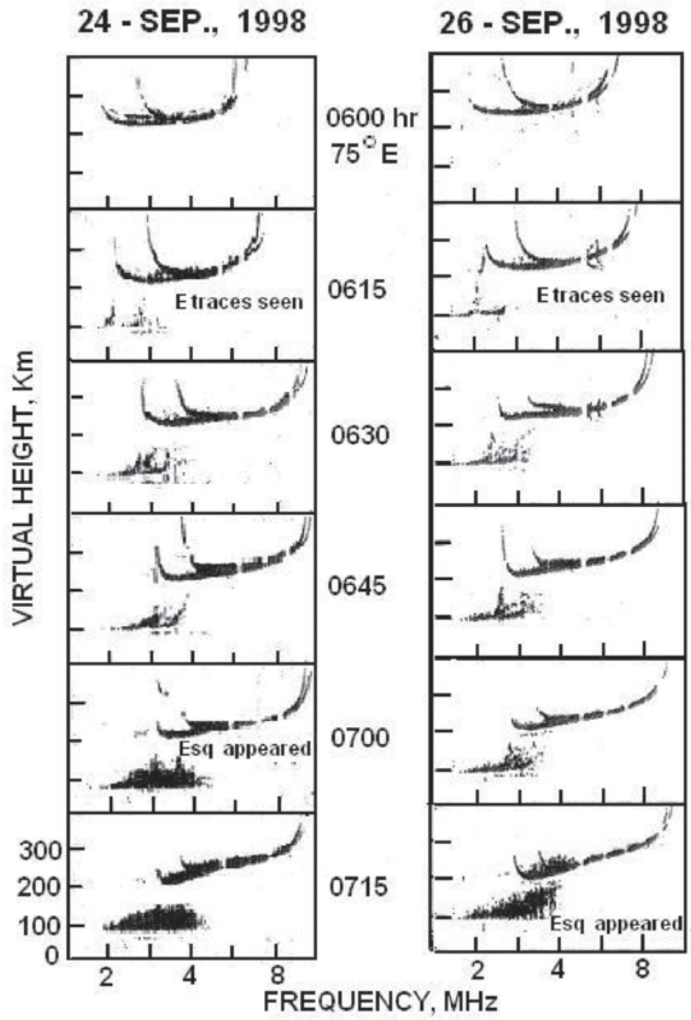


Figure 10. Quarter hourly ionograms from 0600h to 0715h (LT) at Thumba on 24 and 25 September 1998.

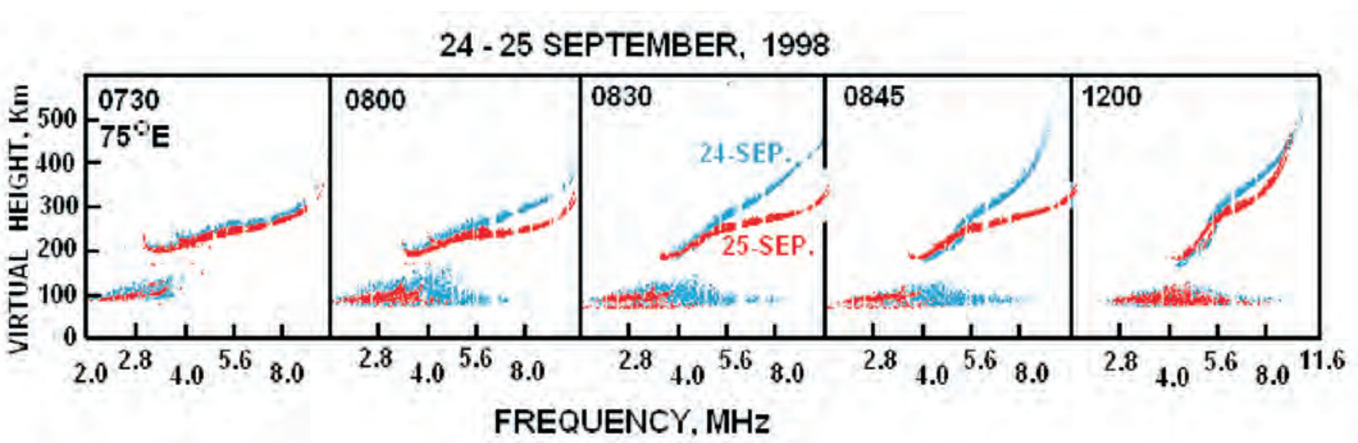
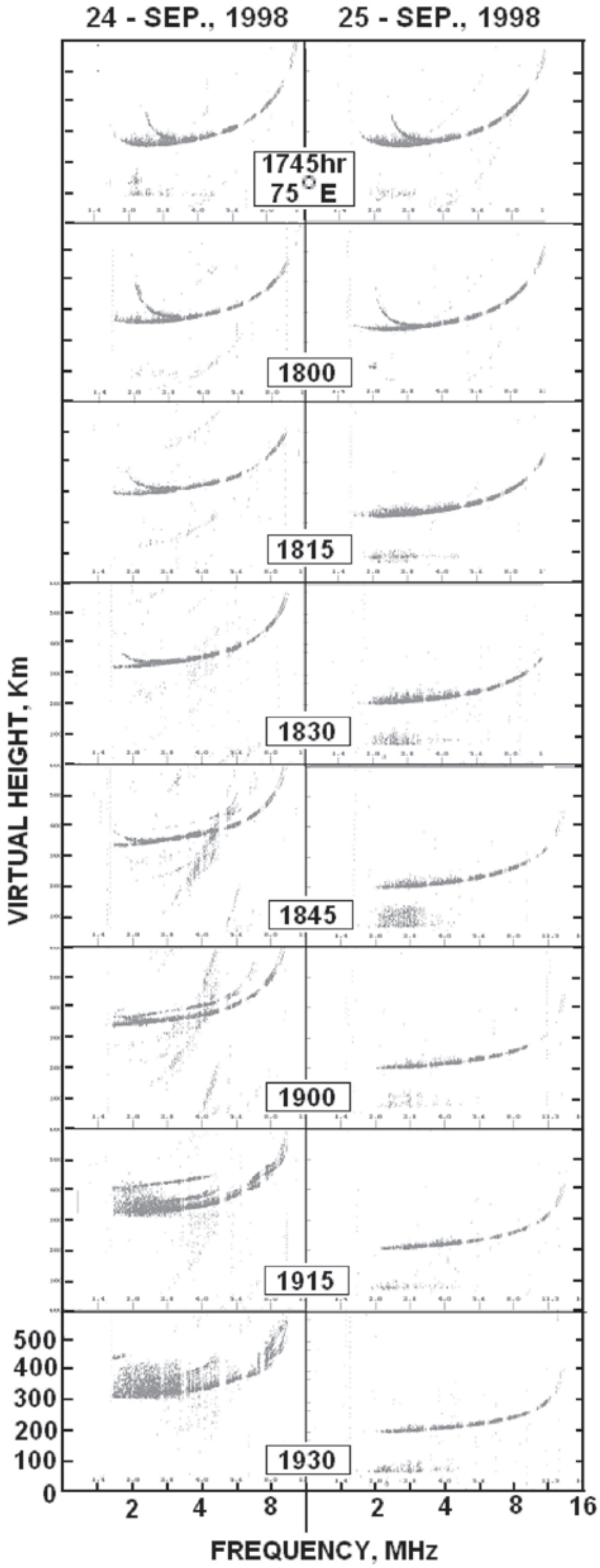


Figure 11. Selected ionograms at Thumba on 24 and 25 September 1998 (superimposed) showing the effects of counter electrojet in the pre-noon hours on 25 September 1998; absence of Esq and F-layer at lower altitudes due to the counter electrojet.



Figuew 12. Quarter hourly ionograms from 1745h to 1930h (LT) at Thumba on 24 and 25 September 1998. Note the post-sunset height rise of F-layer and onset of spread-F on 24 September and no height rise and absence of spread-F on 25 September due to the afternoon counter electrojet on the latter day.

0600h show F layer with group retardation in the beginning indicating fresh ionization below in the E-region. At 0615h the F region traces were normal and the E region traces with weak sporadic E echoes at 100 km also seen on 24 September. The sporadic E layer echoes were fairly strong at 0630h but no slant echoes were recorded to give the triangular configuration of E_{s-q}. Equatorial type of sporadic-E developed at 0700h on 24 September. However on 25 September the scatter signals were completely absent. It appeared at 0715h but became very weak later. Strong equatorial sporadic E echoes were recorded in the ionograms only after 0930h 0430 UT). The disappearance of sporadic-E on 25 September 1998 has been reported earlier (Rastogi and Chandra 2009).

The presence of the irregularities depends both on the direction of the gradient in ionization and of the electric field. For the upward plasma density gradient electric field has to be eastward for the gradient drift instability to operate. Thus the late appearance of the q type of sporadic-E on 25 September 1998 is due to the counter electrojet in the morning.

The selected daytime ionograms at Thumba on the two days are shown in Fig. 11.

The ionograms are superimposed and shown with different colours. At 0715h the two ionograms are similar. At 0800h there are differences. The sporadic-E traces are stronger for 24 September but on 25 September one can see only E-layer traces. The F-layer height is considerably lower on 25 September. Ionograms at 0830 and 0845h also show strong sporadic-E on 24 September only. The difference in the heights of F-layer on two days becomes more pronounced. At 1200h the two ionograms become almost similar. Thus the counter electrojet gives rise to absence of equatorial Es and lowering of F-layer in the forenoon hours of 25 September.

An examination of the quarter hourly ionograms on 24 and 25 September in the post-sunset and night hours is made to study the onset of spread-F. Fig. 12 shows selected ionograms at Thumba on the two days in the evening and pre-midnight hours. At 1745h the ionograms on the two days look quite similar with h′F and f_oF_2 in similar range. At 1800h one can note significant differences. The h′F is lower on 25 September 1998 and highest on 24 September and reverse is true for f_oF_2 (higher on 25 September). This trend is seen at later hours also. Thus on 25 September there is no post-sunset height rise and ionization anomaly. Subsequent to the height rise on 24 September spread-F develops but on 25 September there is no height rise and no spread-F. High multiples are seen at 1845h on 24 September but not on 25 September. Presence of high multiples is considered as a precursor to the onset of spread-F. The onset of spread-F at 1915h with spreading at lower frequencies is also preceded by satellite traces at 1900h. At 1930h spread-F is fully developed. This is typical of the onset of spread-F at Thumba. On 26 September spread-F at lower frequencies is seen at 1900h and fully developed spread-F by 1945h. Spread-F was seen till 2200h on 24 September. Frequency type of spread-F was later seen from 2330h to midnight (not shown here). Thus spread-F was present as normal on 24 September 1998 but on 25 September it was inhibited due to the magnetic storm.

Sobral et al. (1997) studied the effects of intense storms and sub-storms on equatorial F-region parameters during equinoctial months of 1978-79 to identify the responses of prompt penetration electric fields and of the delayed disturbance dynamo electric fields. They showed that at times the two effects may compete and cause partial or complete cancellation of the effects. Sastri et al., 2000 showed the prompt penetration electric field causing the CEJ and absence of anomaly on the morning of 4 November 1993 in the Indian longitude sector. Sastri, Niranjan & Subba Rao (2002) reported abnormal midnight descent of F-region westward electric field) in the Indian sector associated with the severe magnetic storm of 15 July 2000 interpreted as a signature of the prompt penetration electric field. This occurred near simultaneous with the eastward electric field disturbance in the dusk sector reported by Basu et al., (2001). The prompt penetration electric field in both the longitude sectors occurred in an environment under the influence of disturbance dynamo. Tulasi Ram et al., (2008) reported response of post sunset ESF during few geomagnetic storms combining data from Indian sector and other longitude sectors covering 92°.

Veenadhari et al., (2010) have recently reported an enhancement of EIA during the main phase and its reduction during the recovery phase of the storms associated with the penetration of magnetospheric electric fields to the magnetic equator during the magnetic storms of 31 March 2001 and 6 November 2001.

The space weather event of 24-25 September 1998 presents a unique case with changes in IMF-Bz in association with enhanced solar wind velocity and density giving rise to a number of counter electrojet and normal counter electrojet conditions right from the local sunrise to post sunset period in the Indian longitude sector. Disappearance and appearance of equatorial type of sporadic-E, absence or presence of the equatorial ionization anomaly coinciding depending on the direction of electric field being westward or eastward and the absence of post sunset rise of F-layer and ESF demonstrate the prompt penetration of electric field arising due to the interplanetary electric field.

CONCLUSIONS

A major space weather event occurred on 25 September 1998 with SC at 2345 UT. Solar wind parameters showed enhanced solar wind velocity and solar wind density associated with the event. Velocity exceeded 600 km/s throughout the day and were almost 900 km/s at local noon. Solar wind density also showed increased density of up to 20 cm^{-3} at 07h LT and 13h LT. Bz component of the IMF turned negative associated with the event with values of about -15 nT in the pre-noon hors. The event gave rise to strong counter electrojet in the morning hours in the Indian sector as seen in the magnetograms and also confirmed by the absence of equatorial type of Es at Thumba. The f_oF_2 values at Thumba in the period 07-10h LT on 25 September were larger than on 24 September, while at Ahmedabad opposite was the case. Thus the strong counter electrojet also resulted in the absence of equatorial anomaly in the pre-noon hours. The high solar wind density at noon with high solar wind velocity resulted in the uplift of F_2 layer at Thumba in the afternoon of 25 September giving rise to anomaly with f_oF_2 values at Ahmedabad higher than on 24 and 26 September. The storm also resulted in counter electrojet in the afternoon hours resulting in no post-sunset height rise of F-layer over Thumba and no spread-F on 25 September.

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